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## Transaction on MECHANICS

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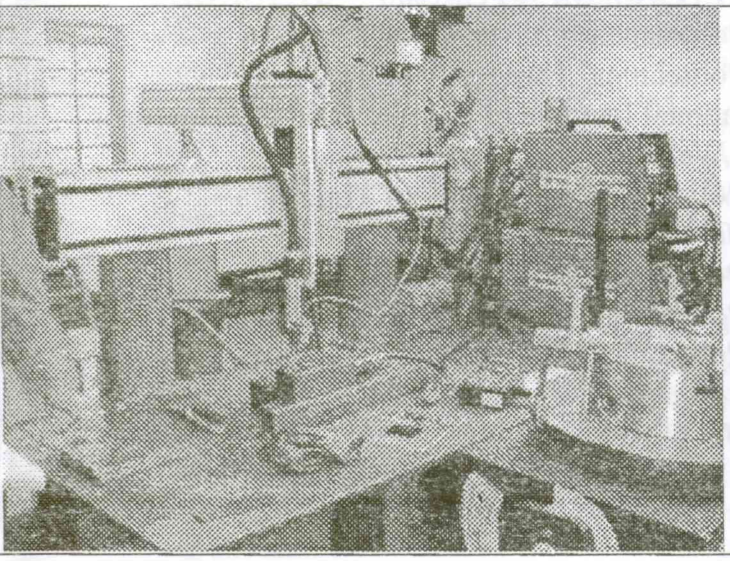

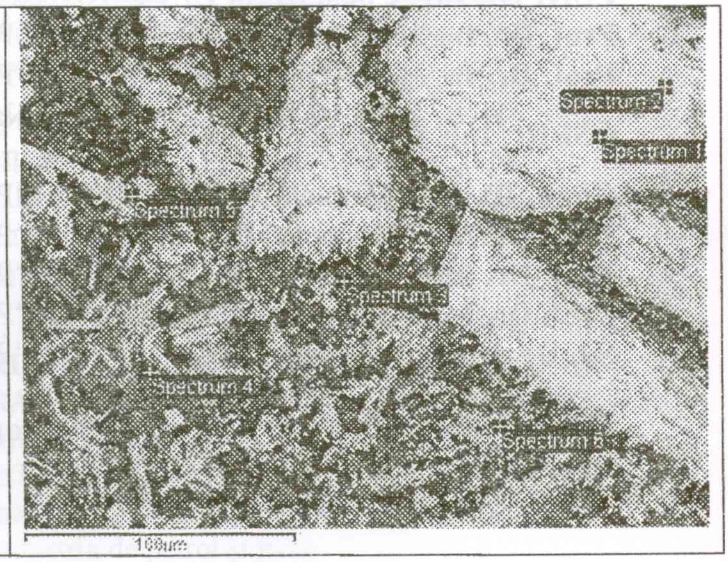


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| | CONTENTS | CUPRINS | |
|---|---|---|---|

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# MATHEMATICAL ANALYSIS OF THE FUNCTION APPROXIMATION FOR THE FORCE GENERATED BY PNEUMATIC ARTIFICIAL MUSCLE

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**Abstract.** The newest and most promising type of pneumatic actuators is the pneumatic artificial muscle (PAM). Different designs have been developed, but the McKibben muscle is the most popular and is made commercially available by different companies (e. g. Fluidic Muscle manufactured by Festo Company). The most often mentioned characteristic of PAMs is the force as a function of pressure and contraction. In this paper our newest function approximation for the force generated by Fluidic Muscles is shown that can be generally used for different muscles made by Festo Company.

**Keywords:** Fluidic Muscle, Force Equation, MS Excel, Solver, Correlation and Regression Analysis

## 1. Introduction

The working principle of different pneumatic muscles is well described in [1, 2, 3, 4, 5, 6]. PAMs have various names in literature: Pneumatic Muscle Actuator, Fluid Actuator, Fluid-Driven Tension Actuator, Axially Contractible Actuator, Tension Actuator, etc. [3, 4, 7].

Most types of PAMs consist of a rubber bladder enclosed within a helical braid that is clamped on both ends. A PAM's energy source is gas, usually air. The muscle will expand radially and contract axially when inflated, while generating high pulling forces along the longitudinal axis. The tensile force depends on the contraction and the pressure of actuator (Figure 1). This feature is totally different from pneumatic cylinders, because a cylinder develops a force that depends on the applied pressure and piston surface area and independent from displacement [4].

Typically, the air muscle can contract by about 25 % of its initial length.

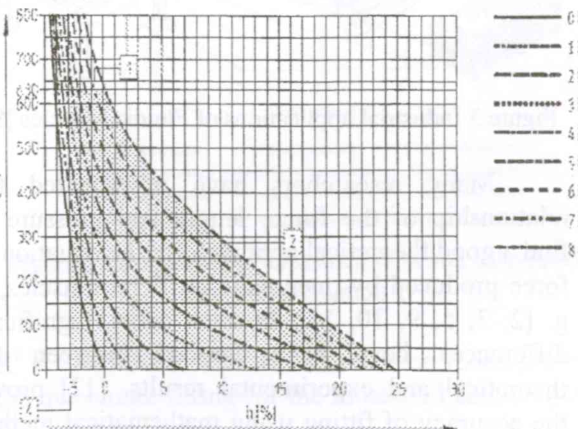


Figure 1 Isobaric force-contraction characteristics of Fluidic Muscle with inner diameter of 10 mm [8]

Where:
1 - Maximal force,
2 - Maximal operating pressure,
3 - Maximal deformation (contraction),
4 - Maximal pretensioning.

Figure 2 shows several Fluidic Muscles and industrial applications of them can be seen in Figure 3: drive for punching, belt edge control for winding processes, lifting device and drive for a vibratory hopper.

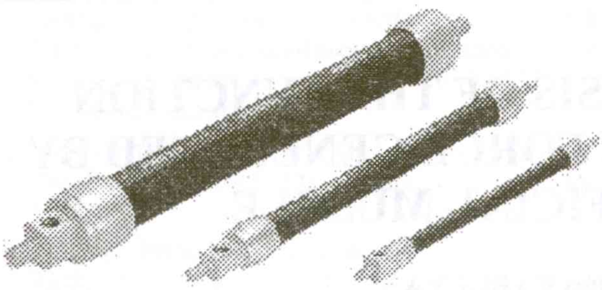

Figure 2 Fluidic Muscles made by Festo Company

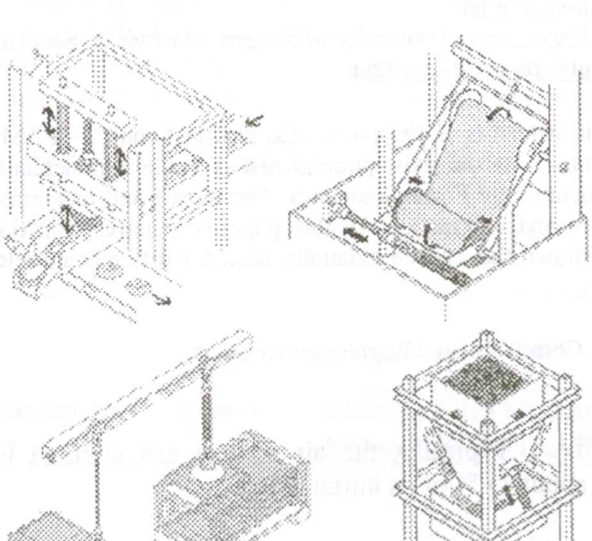

Figure 3 Industrial applications of Fluidic Muscles [8]

Many researchers have investigated the relationship of the force, length and pressure to find a good theoretical approach for the equation of force produced by pneumatic artificial muscles, e. g. [2, 3, 5, 9, 10, 11]. In most cases, significant differences have been noticed between the theoretical and experimental results. [12] proves the accuracy of fitting using mathematical method of statistics (correlation index R = 0.998-0.999), only, but it is valid for SAM (Shadow Air Muscle) made by Shadow Robot Company.

The layout of this paper is as follows. Section 2 (Materials and Methods) is devoted to illustrate the static models on the basis of professional literature and our new force models. Section 3 (Experimental Results) presents comparisons between the measured and theoretical data. Finally, section 4 (Conclusions and Future Work) gives the investigations we plan.

For this study Fluidic Muscle type DMSP-10-250N-RM-RM (with inner diameter of 10 mm and initial length of 250 mm) produced by Festo Company is selected.

## 2. Materials and Methods

The general behaviour of PAM with regard to shape, contraction and tensile force when inflated depends on the geometry of the inner elastic part and of the braid at rest (Figure 4), and on the materials used [3]. Typical materials used for the membrane construction are latex and silicone rubber, while nylon is normally used in the fibres. Figure 5 shows the structure of Fluidic Muscles.

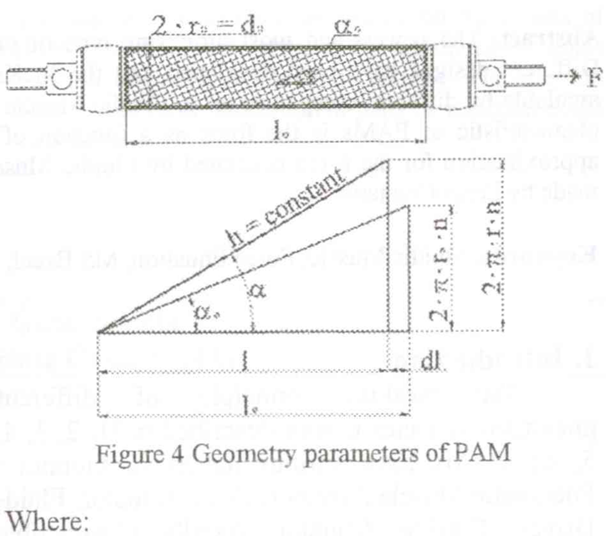


Figure 4 Geometry parameters of PAM

Where:
$F$ the pulling force,
$r_0$ the initial inner radius of PAM,
$l_0$ the initial length of PAM,
$\alpha_0$ the initial angle between the thread and the muscle long axis,
$r$ the inner radius of the PAM when the muscle is contracted,
$l$ the length of the PAM when the muscle is contracted,
$\alpha$ the angle between the thread and the muscle long axis when the muscle is contracted,
$h$ the constant thread length,
$n$ the number of turns of thread.

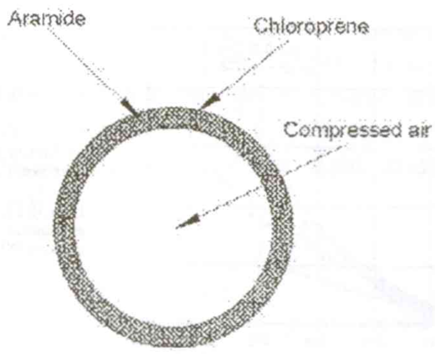


Figure 5 Structure of Fluidic Muscles

Good description of the general static model of PAMs can be found in [2, 3, 5]. On the basis of them the force equation is found:

$$F(p, \kappa) = p \cdot \pi \cdot r_0^2 \cdot (a \cdot (1-\kappa)^2 - b) \tag{1}$$

Where:

$a = \dfrac{3}{tg^2 \alpha_0}$,

$b = \dfrac{1}{\sin^2 \alpha_0}$,

$\kappa$ the contraction and $\kappa = \dfrac{l_0 - l}{l_0}$,

$p$ the applied pressure.

Equation 1 was modified by Tondu and Lopez in [5] and Kerscher et al. in [11] with correction factors $\varepsilon$ and $\mu$:

$$F(p, \kappa) = \mu \cdot p \cdot \pi \cdot r_0^2 \cdot (a \cdot (1 - \varepsilon \cdot \kappa)^2 - b) \tag{2}$$

Where:

$\varepsilon = a_\varepsilon \cdot e^{-p} - b_\varepsilon$,

$\mu = a_\kappa \cdot e^{-\kappa \cdot 40} - b_\kappa$.

Significant differences between the theoretical and experimental results using equation 1 and equation 2 were proved in [13] and [14]. To eliminate the differences new approximation algorithms with six and five unknown parameters have been introduced for the force generated by Fluidic Muscles:

$$F(p, \kappa) = (a \cdot p + b) \cdot e^{c \cdot \kappa} + d \cdot p \cdot \kappa + e \cdot p + f \tag{3}$$

$$F(p, \kappa) = (p + a) \cdot e^{b \cdot \kappa} + c \cdot p \cdot \kappa + d \cdot p + e \tag{4}$$

Equation 3 can be generally used with high accuracy for different Fluidic Muscle independently from length and diameter under different values of pressure and equation 4 can be used with high accuracy for Fluidic Muscle with inner diameter of 20 mm, only.

The unknown parameters of equation 3 (a, b, c, d, e and f) and equation 4 (a, b, c, d and e) can be found by Solver in MS Excel 2010.

Accurate fitting of equation 3 and equation 4 for Fluidic Muscles with inner diameter of 20 mm was analysed in [15, 16, 17].

## 3. Experimental Results

The analyses were carried out in MS Excel environment. Tensile force of Fluidic Muscles under different values of constant pressure is a function of muscle length (contraction) and air pressure. The force always drops from its highest value at full muscle length to zero at full inflation and position.

Firstly, the measured data and calculated data using equation 1 were compared. As it is shown in Figure 6, there is only one intersection point between the measured and calculated results and no fitting.

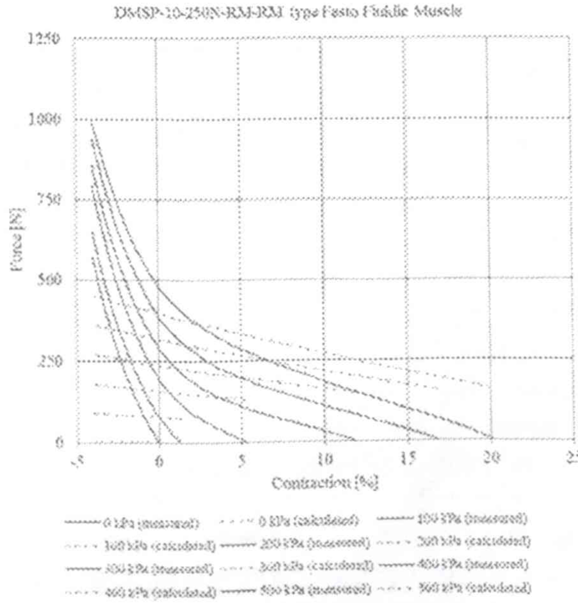


Figure 6 Comparison of measured data and calculated data using equation 1

$R^2 = 0.413 \rightarrow R = 0.6427$ correlation index proves the inaccurate fitting for the measured data (Figure 7).

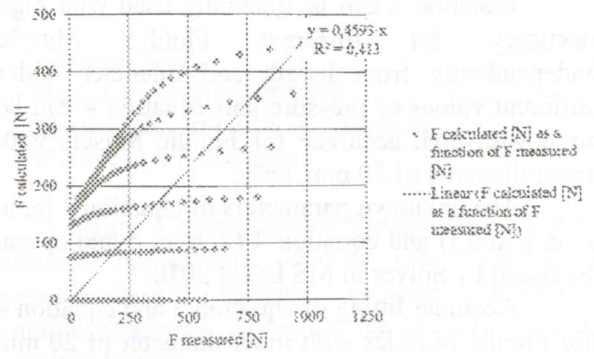


Figure 7 Relationship between the measured force and calculated force using equation 1

In the interest of fitting the simulation was repeated with equation 2 (Figure 8). The coefficients ($a_\kappa$, $b_\kappa$ $a_\varepsilon$, and $b_\varepsilon$) of equation 2 were found using Solver in MS Excel. Values of unknown parameters of equation 2 are listed in Table 1.

Table 1 Values of unknown parameters of equation 1

| Parameters | Values |
|---|---|
| $a_\kappa$ | 0.219201983 |
| $b_\kappa$ | -0.530552613 |
| $a_\varepsilon$ | 5.22351E+29 |
| $b_\varepsilon$ | -3.754278241 |

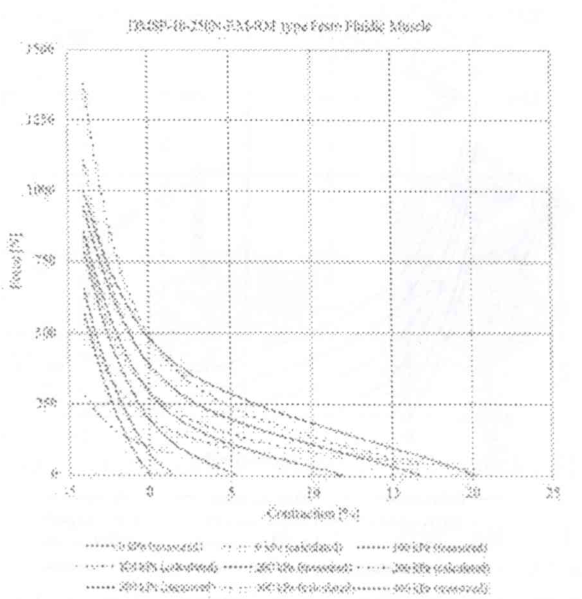


Figure 8 Comparison of measured data and calculated data using equation 2

Figure 8 shows the measured and calculated results still do not fit. Better fitting was attained, but at a pressure of 0 kPa we still have a rather substantial inconsistency. This inconsistency can be seen in Figure 9 ($R^2$ = 0.6278 → R = 0.7923 correlation index).

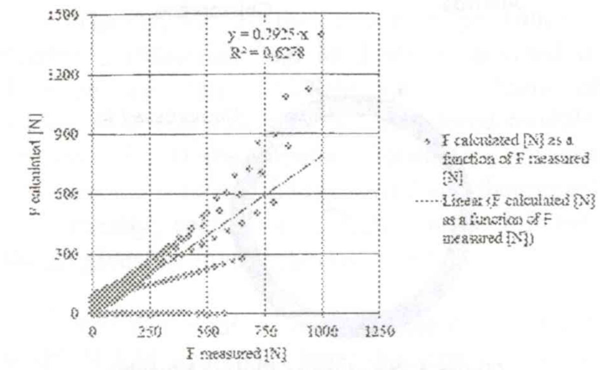


Figure 9 Relationship between the measured force and calculated force using equation 2

To improve fitting quality under different values of pressure including 0 kPa new approximation algorithms have been introduced with six and five parameters (equation 3 and equation 4). The unknown parameters of equation 3 and equation 4 can be found using Solver in MS Excel, too. Values of unknown parameters of equation 3 are shown in Table 2.

Table 2 Values of unknown parameters of equation 3

| Parameters | Values |
|---|---|
| a | -9.2194029 |
| b | 203.7012413 |
| c | -0.34221042 |
| d | -3.2255991 |
| e | 109.2038216 |
| f | -208.372034 |

The accurate fitting of equation 3 can be seen in Figure 10.

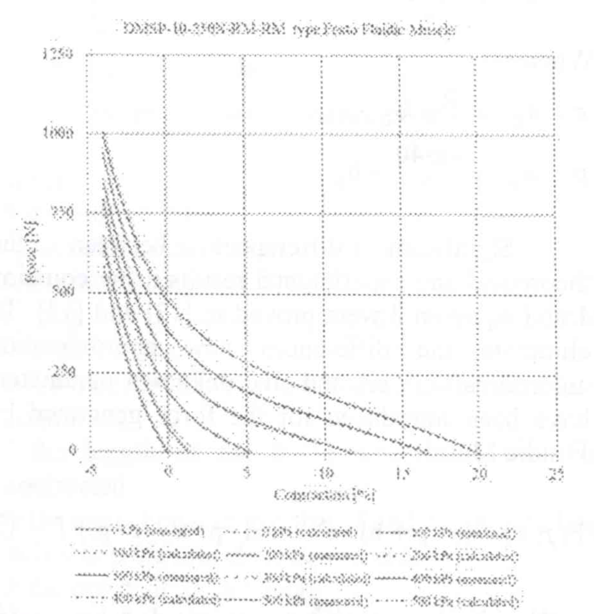


Figure 10 Comparison of measured data and calculated data using equation 3

As we can see we have consistent fitting even at a pressure of 0 kPa. Figure 11 illustrates the relationship between the measured force and calculated force. The $R^2 = 0.9978 \rightarrow R = 0.9989$ correlation index proves the tight relationship between them.

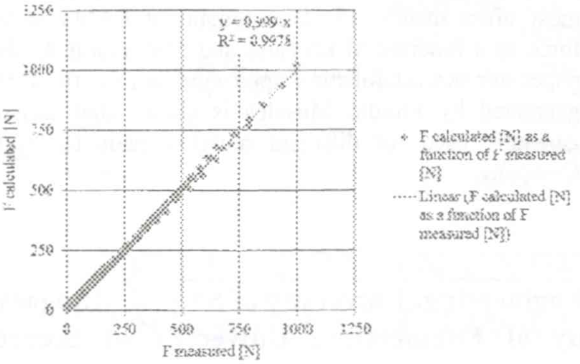


Figure 11 Relationship between the measured force and calculated force using equation 3

## 4. Conclusions and Future Work

In this work new functions for the force generated by Festo Fluidic Muscle were introduced and the accuracy of approximation algorithm with six unknown parameters was proved. The investigations were carried out in MS Excel environment. Our main aim is to develop a new general mathematical model for pneumatic artificial muscles applying our new models and results.

## References


1. D. G., Caldwell, A., Razak, M. J., Goodwin, *Braided Pneumatic Muscle Actuators*, IFAC Conference on Intelligent Autonomous Vehicles, Southampton, United Kingdom, 18-21 April, 1993, p. 507-512
2. C. P., Chou, B., Hannaford, *Measurement and modeling of McKibben pneumatic artificial muscles*. IEEE Transactions on Robotics and Automation, Vol. 12, No. 1, 1996, p. 90-102
3. F., Daerden, *Conception and realization of pleated artificial muscles and their use as compliant actuation elements*. PhD Dissertation, Vrije Universiteit Brussel, Faculteit Toegepaste Wetenschappen Vakgroep Werktuigkunde, 1999, p. 5-33
4. F., Daerden, D., Lefeber, *Pneumatic artificial muscles: actuator for robotics and automation*. European Journal of Mechanical and Environmental Engineering, Vol. 47, 2002, p. 10-21
5. B., Tondu, P., Lopez, *Modeling and control of McKibben artificial muscle robot actuator*. IEEE Control System Magazine, Vol. 20, 2000, p. 15-38
6. M., Balara, A., Petík, *The Proporties of the Actuators with Pneumatic Artificial Muscles*. Journal of Cybernetics and Informatics, Vol. 4, 2004, p. 1-15
7. R., Ramasary, M. R., Juhari, M. R., Mamat, S., Yaacobs, N. F., Mohd Nasir, M., Sugisaka, *An Application of Finite Modelling to Pneumatic Artificial Muscle*. American Journal of Applied Sciences, Vol. 2, No. 11, 2005, p. 1504-1508
8. Festo: *Fluidic Muscle DMSP, with Press-fitted Connections*. Fluidic Muscle MAS, with Screwed Connections, Festo Product Catalogue, 2005, p. 39
9. N., Tsagarakis, D. G., Caldwell, *Improved Modelling and Assessment of Pneumatic Muscle Actuators*. IEEE International Conference on Robotics and Automation, San Francisco, CA, USA, 24-28 April, 2000, p. 3641-3646
10. R. W., Colbrunn, G. M., Nelson, R. D. Quinn, *Modeling of Braided Pneumatic Actuators for Robotic Control*. International Conference on Intelligent Robots and Systems (2001 IEEE/RSJ), Maui, HI, USA, 29 October - 03 November, 2001, p. 1964-1970
11. T., Kerscher, J., Albiez, J. M., Zöllner, R., Dillmann, *FLUMUT - Dynamic Modelling of Fluidic Muscles using Quick-Release*. 3rd International Symposium on Adaptive Motion in Animals and Machines, Ilmenau, Germany, 25-30 September, 2005, p. 1-6
12. J., Borzikova, M., Balara, J., Pitel, *The Mathematical Model of Contraction Characteristic k = (F, p) of the Pneumatic Artificial Muscle*. XXXII. Seminar ASR '2007 „Instruments and Control", Farana, Smutný, Kočí & Babiuch, Ostrava, Czech Republic, 27 April, 2007, p. 21-25
13. J., Sárosi, Z., Fabulya, *New Function Approximation for the Force Generated by Fluidic Muscle*. International Journal of Engineering, Annals of Faculty of Engineering Hunedoara, 2012, Vol. 10, No. 2, p. 105-110
14. J., Sárosi, Z., Fabulya, G., Szabó, P., Szendrő, *Investigations of Precise Function Approximation for the Force of Fluidic Muscle in MS Excel*. Review of Faculty of Engineering (International Conference on Science and Technique in the Agri-Food Business, ICoSTAF 2012), Vol. 2012/3-4, p. 1-8
15. J., Sárosi, *New Approximation Algorithm for the Force of Fluidic Muscles*. 7th IEEE International Symposium on Applied Computational Intelligence and Informatics (SACI 2012), Timisoara, Romania, 22-24 May, 2012, p. 229-233
16. J., Sárosi, *Newest Approach to Modeling Hysteresis in the Force-Contraction Cycle of Pneumatic*

*Artificial Muscle*. Acta Technica Corviniensis, Bulletin of Engineering, Vol. 5, No. 4, 2012, pp. 63-66

17. J., Sárosi, *New Force Functions for the Force Generated by Different Fluidic Muscles*. SCIENTIFIC BULLETIN of The "POLITEHNICA" University of Timişoara, Romania, Transactions on AUTOMATIC CONTROL and COMPUTER SCIENCE (in press)

## ANALIZA MATEMATICĂ A FUNCŢIEI DE APROXIMARE A FORŢEI GENERATE DE UN MUSCHI PNEUMATIC ARTIFICIAL

**Rezumat**

The newest and most promising type of pneumatic actuators is the pneumatic artificial muscle (PAM). Different designs have been developed, but the McKibben muscle is the most popular and is made commercially available by different companies (e. g. Fluidic Muscle manufactured by Festo Company). The most often mentioned characteristic of PAMs is the force as a function of pressure and contraction. In this paper our newest function approximation for the force generated by Fluidic Muscles is shown that can be generally used for different muscles made by Festo Company.

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